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Project Galileo
The Europa Mission

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PROJECT GALILEO: THE EUROPA MISSION

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Abstract

The Galileo Spacecraft completed its primary mission on December 7, 1997. However, funding was approved at a reduced level to continue operations into an extended mission based on the excellent health of the spacecraft, and the desire to continue exploration of the Galilean satellite Europa based on the intriguing results found there in the primary mission. The spacecraft has now completed five of its planned eight Europa encounters in the extended mission. Including three encounters earlier in the primary mission, the total of eight close passes by Europa have provided a wealth of new information about this intriguing body, including its interior structure, its interactions with Jupiter's magnetosphere, and its tortured icy surface. These results and the implications they provide relative to a sea of liquid water beneath that ice today are presented.

The engineering aspects of operating the spacecraft over the past year are also presented. The new organization of the flight team and the much reduced staff available in the extended mission, but still operating the same complex spacecraft and attempting to do nearly as much science as in the primary mission, have led to some useful observations and experiences. A recalcitrant attitude control system, due to problems in one of the gyros, has further complicated the daily activities. Another aspect of the extended mission that was recognized at the outset but perhaps not fully appreciated was the fact that the craft is now operating with a total radiation dose exposure well beyond what it was originally designed for. One bonus of the Galileo extended mission is the engineering data being returned describing the spacecraft's performance and survival in this environment that will be very useful to designers of future missions to Jupiter and its satellites. The performance to date in this environment is presented.

1. Introduction

The Galileo Spacecraft has now completed nearly nine years of flight, six in interplanetary cruise and almost three in orbit about Jupiter. Figure 1 shows the path Galileo has taken over this period, first on its interplanetary Venus-Earth-Earth gravity assisted path to reach Jupiter, and then its track as it has moved with Jupiter about one-fourth of the way around the sun since going into orbit around Jupiter in December, 1995. Figure 2 shows the details of Galileo's first eleven orbits that comprise the primary mission, and how the orbits were shaped using the gravitational effects of the Galilean Satellites to proceed from each encounter to the next, while simultaneously achieving the geometries needed to meet the scientific objectives. Figure 3 shows similar details for the path Galileo is now taking as it moves into nearly one year of operations in its two year extended mission.

The past year has been a remarkably successful one for the Galileo Project. The last of the ten satellite encounters planned for the primary mission was completed on November 6, 1997, completing a track record of 100%, ten encounters and ten successes! The return of the data recorded at this last encounter was completed on December 15, 1997. An extended mission, as reported at last year's IAF conference, called the Galileo Europa Mission, or GEM, had already been approved

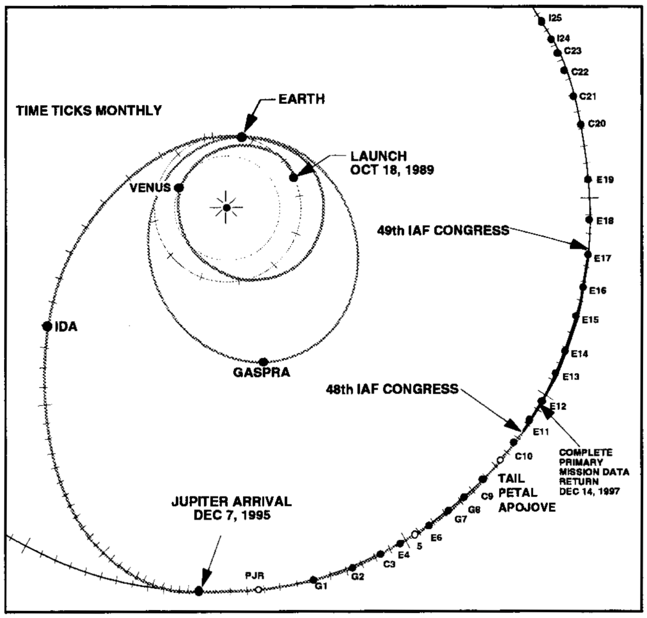

Figure 1. Heliocentric Progress

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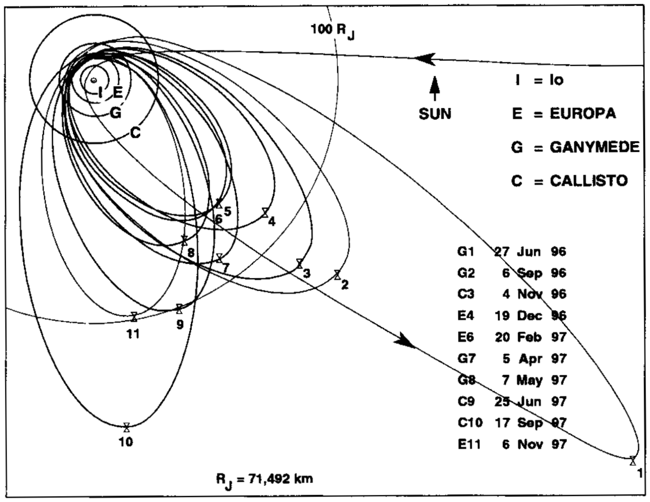

Figure 2. Orbital Tour of the Jupiter System

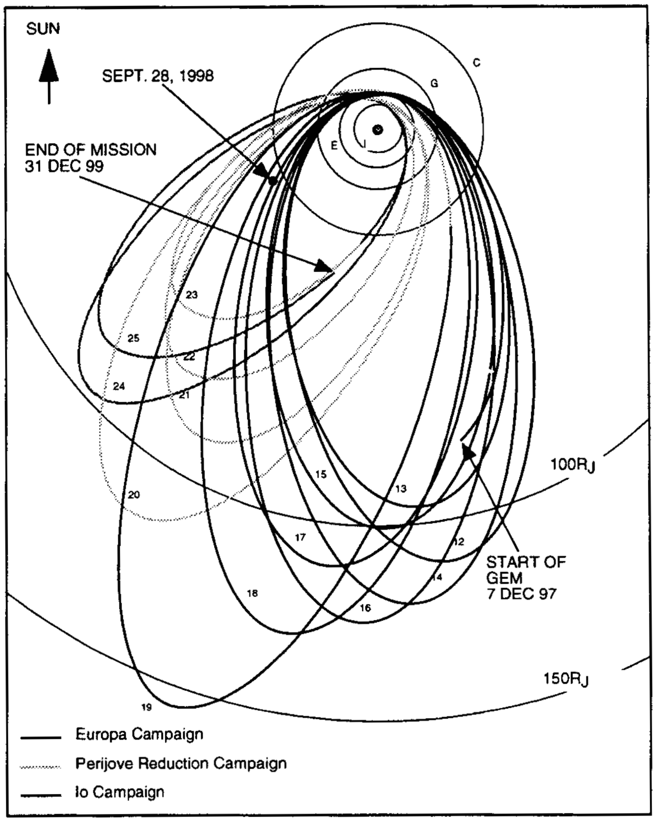

Figure 3. Galileo Europa Mission Tour

by NASA Headquarters, based on the continued normal spacecraft performance, the high interest that the Galileo observations of Europa had raised, and the prospect of obtaining high resolution remote sensing of Io, an objective that had not been fulfilled in the primary mission. This extended mission begins with eight consecutive encounters with Europa, the first of which occurred on December 16, the day after completing the primary mission data return. As of this writing, four of the first five of these encounters have been completed successfully. Some problems that prevented normal data acquisition on the most recent one are described in some detail in the following text. Radiation exposure has always been a concern for the extended mission, because the spacecraft is accumulating a total dosage well beyond what its original design was intended to accommodate. However, to this point, the only radiation induced problem has been in the gyro electronics of the attitude and articulation control system. This problem has caused extra work to accommodate it, but the impacts on data acquisition and return have been rather minimal. Additional details about this problem and the flight team's response to it are described in section 3. The success of the remainder of the mission, consisting of three more Europa encounters, then four with Callisto for the purpose of lowering the perijove distance down to below Io's orbital distance, and finally two close encounters with Io, is by no means assured because of the threats of further radiation induced failures. However, all systems are operating satisfactorily at this time, and the prospects for a fully satisfactory extended mission completion look very favorable.

2. The Mission Transition

The substantially reduced level of funding available to the Galileo Project in its extended phase as compared to its primary phase dictated some significant changes in the way the Project would be operated. There were two significant factors that mitigated considerably the effect this reduction would have on the extended mission's ability to acquire and return science data. The first was the ability to take advantage of the skills and experience of the prime mission staff prior to the descoping of the team to develop a very careful and detailed plan for the science observations that would be taken in the extended mission. This plan was complete through the last of the Callisto encounters, and only omitted the Io encounters. The existence of this plan for the GEM team significantly reduced the needed up-front planning work, and permitted the development of the data acquisition sequences with the much reduced staff. The omission of the Io encounters in this plan was deliberate, in recognition that the numerous planned distant observations of Io during the earlier part of the GEM would undoubtedly influence the observations that would be desired, thus at least partially invalidating any plans that would have been developed.

The second mitigating factor was the fact that the GEM operations team was formed from the existing prime mission staff. With virtually no exceptions, the team members that are now running the GEM were also on the prime mission team, and in almost all cases, they supported the prime mission for at least as long as the two years of the prime orbital mission. This very experienced team that knew the spacecraft, the processes, the tools, and each other very well, was able to pick up the science plan developed by the prime mission team, and keep going with the science data collection to a significant percentage of the level established in the prime mission.

3. Orbiter Performance Overview

3.1 Attitude and Articulation Control Subsystem (AACS)

The Attitude and Articulation Control Subsystem hardware and software have performed excellently for the past year with the exception of a gyro electronics problem (see 4.2 for more details). There has been no evidence of other components degrading due to radiation in the last year, although this may well change as the extended mission progresses. Since the gyro electronics variation was first evident in December 1997, there have been a number of minor anomalies resulting from gyro output changes or the precautions put in place as a result of the gyro changes. Both the E12 and E15 encounters executed as expected with small pointing differences. Orbit Trim Maneuvers 39 and 47 produced the required changes in the trajectory despite unplanned changes in spacecraft configuration during their execution. In all cases, normal spacecraft activity resumed almost immediately and the impact to science observations was minimal.

3.2 Command and Data Subsystem (CDS) and Tape Recorder Subsystem (DMS)

The Command and Data Subsystem is the primary "brain" of the spacecraft and it continues to be reasonably healthy. Despite increasing radiation exposure, there have been no new RAM bit failures. Unfortunately, there has been a burst of three transient bus resets just prior to the Europa 16 encounter, which prevented the planned science observations recording. These transient bus resets were identical to prior incidents, which came in clusters of from three to five. There has also been a slight increase in the temperature variations on the despun CDS as part of the gyro electronics work-around. These thermal cycles have not had any impact since each additional cycle results in less than 0.5% usage of CDS lifetime. The tape recorder used for storing data continues to record and play back data satisfactorily. To ensure that this continues to be the case, command sequences are still being carefully built to follow the "how to use the tape recorder" rules that have been in place since before orbital operations began. In addition, a four-track tape recorder conditioning is performed approximately every thirty days. The number of tape start/stop cycles now exceeds the lifetime specification, but no impact has been observed from this increased activity. Should any fatal tape recorder problems occur, a limited "non-tape recorder" operating plan is in place.

3.3 Transient Bus Reset Anomaly

During the Europa-16 encounter on July 20, 1998, a series of three transient bus resets occurred on the spacecraft. These caused the spacecraft to enter the safe mode, halting the science data gathering sequence just prior to the beginning of the Jupiter and Europa closest approach periods. After diagnosis of the problem, the spacecraft was recovered to normal operations and playback began of the limited set of science observations that were recorded prior to the anomaly. This series of transient bus resets appears to be identical to the prior clusters last seen in September, 1993. The prior resets appeared in clusters of from three to five events, spaced as far apart as 17 weeks. Debris generated in the slip rings is believed to be the cause of these events, and the events should decrease in frequency as the slip rings continue to wear in.

3.4 Power/Pyrotechnic Subsystem (PPS)

The Power/Pyrotechnic subsystem continues to provide power to the spacecraft's systems and instruments as expected. In the past year, the Radioisotope Thermoelectric Generator (RTG) power output has decayed from 475 watts to 467 watts, which closely matches the RTG lifetime decay profile. As the Europa mission continues and less power is available, more choices have to be made between keeping spacecraft components properly warm and having the available power to operate the science instruments. Given this situation, heater configurations have been changed to provide a balance between the risk of component failure and the reward of full science operation.

3.5 Rocket-Propulsion Module

The Rocket Propulsion Module (RPM) continued its fine performance of the previous year. From the C10 encounter (9/17/97) until August 18th, a total of 19 Orbit Trim Maneuvers (OTMs) has been performed (OTM-33 through OTM-51) to keep the spacecraft on its planned flight path. In addition, the RPM continued to perform thruster flushes, spin and pointing corrections, and attitude maintenance turns. None of the propulsive activities showed any variation in thruster performance nor were there any RPM anomalies or hardware failures during this time. After all of the above events, propellant reserve is still excellent with 26 kg (at the 90% confidence level) expected to be available at the time of the second Io encounter (Io 25).

3.6 Temperature Control Subsystem

The Temperature Control Subsystem is performing very well at keeping the spacecraft thermally viable. One of the most important areas to be thermally balanced is the despun portion of the CDS computer in Bay A. The temperature of Bay A can have an impact on the CDS since there are solder joints within the computer that are sensitive to temperature variations. The less thermal cycles on Bay A, the better. Bay A's temperature is also impacted by the power dissipation from Bays B, C and D. In an effort to maintain Bay A temperature, the heaters within Bays B,C and D are being kept on as long as power permits. In the last year, Bay B has been subject to additional thermal variations since the inertial electronics (INS) are in Bay B and the gyro electronics anomaly has led to having the INS off for short periods of time. Some parts of the spacecraft are reaching temperatures that are close to their lower allowable limit without operational impact.

In the Europa mission, these allowable temperature requirements have necessarily been relaxed. However, given the margin on these limits, operating with colder components has not been a problem.

3.7 Telecommunications Subsystem

The telecommunications subsystem is operating as expected using the low gain antenna. Of the performance variations seen earlier in the mission, there continues to be an ongoing slow decline in the LGA drive telemetry (although no apparent loss of transmitted power) and a changing Ultra Stable Oscillator frequency.[1] There has been no further indication of variation in the Voltage Control Oscillator (VCO) since September 1996.[1] Given the stable performance of the telecommunications system and the limited commanding resources in the Europa mission, no further telecom calibrations are planned.

4. Non-Instrument Anomalies

4.1 Continuous DMS Search Anomaly

On September 17, 1997, the spacecraft was playing back C9 data from the DMS when the tape recorder went into a continuous search mode. This condition means the CDS is searching the tape for the next valid entry to continue playing back data. The search continued through tracks 3, 4, 1 and 2 since ground-based diagnosis was delayed by an unplanned gap in the tracking coverage. Once the anomaly was understood, it was clear that the next valid entry time did not as yet exist since the expected data had not yet been put on the tape. The problem was resolved in time to complete the next planned recording and a new ground check was implemented to preclude further problems of this nature.

4.2 Gyro Electronics Anomaly

During the E12 encounter on December 15, 1997, AACS started to experience the first of a series of anomalies that would eventually be diagnosed as a problem in the gyro electronics circuitry that may be attributable to radiation effects. The fundamental symptom of the problem is an inaccurate rendition from the gyros of how far the spacecraft's attitude has changed (if at all) during attitude turns, maneuvers, and scan platform motion. While the cause of this discrepancy in gyro output was under investigation, precautions were put in place for any propulsive spacecraft activities to ensure that no autonomous changes in spacecraft attitude would occur based on erroneous gyro information. Initial diagnostics showed one of the gyro axes producing 9% more pulses than expected when sensing motion in a specific direction. This number later increased to 21% after the E13 encounter. The gyros are controlled by the Inertial Electronics (INS) on the despun portion of the spacecraft. The raw data from the gyros is converted into an angular rate in the gyro electronics within the INS. For each gyro axis there is an A-D converter which in turn houses two analog driver chips (DG181)—one for each of the negative and positive axes directions. Each DG181 contains two JFET (Field Effect Transistor) switches. It appears the problem is with one of the JFET switches leaking while in an OFF (open) position. This anomalous behavior has been seen before in radiation conditions and is consistent with one axis producing too many pulses. An AACS flight software patch was uplinked to the spacecraft in mid-May 1998 to address the problem. After the raw gyro data is processed, a series of scale factors is applied to compensate for gyro bias and drift. This portion of the code was rewritten to account for gyro degradation and to allow different scale factors to be applied to the positive and negative axes directions. Given the possibility that degradation may occur on the other gyro axes as well, the implemented change was made on all gyro axes. The scale factors on-board closely match the current gyro performance and will be updated should further change occur. Gyro performance tests are now being scheduled twice during each orbit to characterize gyro changes and allow parameter updates before the next encounter. This flight software change effectively corrects the gyro electronics anomaly. One remaining operational complication occurs on orbits where the satellite encounter is post perijove. In those cases the gyros might worsen during the perijove radiation pass before the flyby and thus before the parameters can be updated. In an effort to mitigate this, the Inertial Electronics are being turned off for up to 12 hours around closest approach—minimizing the effects of radiation exposure to the electronics. Investigation continues to validate the failure scenario that involves the JFET switches and to understand if radiation is the most likely suspect.

5. Instrument Status

Overall, the Galileo instruments are working very well. Only one instrument has a major limitation on its data taking capability, and current plans now accommodate that limitation. Since the last report of Galileo's activities, three instruments have had anomalies—the Energetic Particles Detector (EPD), the Near Infrared Mapping Spectrometer (NIMS), and the Plasma Wave Subsystem (PWS).

During the Europa 12 perijove pass, the EPD instrument halted. Investigation showed the problem to be a transient memory corruption, probably due to radiation. The instrument lost the Europa 12 data taking opportunity, but was back up and taking data successfully during the Europa 14 and subsequent encounters. In addition, during the recovery from the Europa 16 transient bus reset safing anomaly, the instrument stopped scanning and entered standby mode. Investigation is continuing, but it is believed that this is the expected response of the instrument to the safing. The instrument was reconfigured and is now operating properly.

As previously reported, the NIMS instrument has experienced two types of failures. It has lost two of its 17 detectors, and it experiences periodic software halts during data taking. As of the previous report, the NIMS had experienced an average of one halt per perijove pass. This trend continues, but represents only minor losses to the investigation's data taking. Additionally, a problem with the NIMS on-board data compression processing in the CDS surfaced during the E12 playback. Use of an incompletely checked out playback editor feature called "rate control" uncovered a flight software error. This error prevented the NIMS from returning to normal editing mode. The rate control feature ensures that the NIMS playback data is limited to a user defined quantity. If the compression process produces more data than specified, spectrum wavelengths are edited out to achieve the desired quantity of bits returned.

During the Callisto 10 encounter, data from the PWS low frequency magnetic search coil became severely degraded. Subsequent investigation has shown that this portion of the data is virtually useless. However, this part of the plasma wave investigation represents a small portion (approximately 10%) of the overall experiment, and the objectives of this part have largely been previously accomplished. Loss of function in the magnetic coil does not significantly degrade ongoing science goals, and the electric field portion of the PWS instrument is operating nominally, with no problems.

6. Sequence Operations in GEM

Commanding the spacecraft to maintain subsystem and instrument health and safety and to maximize science return within spacecraft and ground resources is the task of Sequence Operations. Commands generated through Sequence Operations may take one of three forms depending on the complexity and time at which all parameters can be defined. The majority of the effort is in designing and implementing orbital sequences, also called background or stored sequences, which are developed in the two to three months preceding execution onboard the spacecraft. These sequences perform all planned spacecraft activity for a period of a few days to a few months, and include science observations, spacecraft attitude maintenance, subsystem and instrument checks, and telemetry management. Mini-sequences and real-time commands which supplement the orbital sequences are used to perform unplanned commanding in response to anomalies or to implement planned activities such as orbit trim maneuvers that cannot be designed months in advance. Playback tables are used to select the recorded science data to be returned and define parameters controlling the onboard data compression process. Sequence Operations in GEM differ from the prime mission as a result of the limited staffing resources and a shorter pre-planning time.

6.1 Orbital Sequences Description

In order to develop sequences in less time and with fewer personnel, the total number of sequences per orbit and their complexity is reduced. Each orbit is divided into two command sequences, encounter and cruise, rather than the three sequences per orbit in the prime mission. Encounter sequences are shorter in duration, three to four days instead of seven or eight, and contain all of science data acquisition, except for a few unique targets of opportunity in cruise. Cruise sequences contain routine spacecraft maintenance and allow for placement of orbit trim maneuvers. Playback of science data recorded during encounter usually starts immediately after the last recorded observation and continues throughout cruise.

Standardization, simplified planning guidelines, and controlling the number of activities by limiting the size of each sequence, as measured by CDS memory bytes, are key to reducing complexity and the work required to design a sequence. Standardization of routine spacecraft maintenance minimizes work needed to continually redefine requirements and simplifies cruise sequence review. A library of pre-generated command sets to perform all routine engineering functions is maintained and used in building the orbital sequences.

Planning guidelines representing the result of trades between ground and spacecraft resources take the form of either identifying the limited set of accepted activities or defining procedural changes. Limiting the number of spacecraft turns for improved science observation geometry and for turn and burn maneuvers to one each in the GEM is an example of the first type of guideline. This restriction drastically cuts the flight team's effort required to identify and verify star sets for celestial reference at the cost of both reduced science optimization and about 5 kg of propellant margin. An example of a procedural simplification that was implemented is to do all of the observation design and sequence development to a single aim point defined at the beginning of sequence development. In the prime mission a nominal aim point was selected within a pre-defined box of possible aim points and the science observation strategy had to be robust to all of the potential flyby geometries. A set of perturbed trajectories modeling the extreme limits of the box was generated by the navigation team and used in prime mission science planning. The propellant cost of selecting the aim point once, at the beginning of development, was very minimal.

Constraining sequence complexity by limiting sequence size decreases the total number of activities. The effect of simplified sequences of shorter duration is seen in the number of remote sensing observation designs going from an average of one hundred eighty per prime mission encounter to between thirty and sixty per GEM encounter depending on whether or not a Jovian atmospheric feature observation was included.

A gyro anomaly early in GEM challenged the a priori assumption of standard operations and exercised the limits of these constraints when the reduced flight team was able to successfully gather anomaly data, support data analysis by outside consultants, generate functional tests and commands responding to related anomalies, design safeguards to minimize the risks of using inertial mode, review sequences in development, and adjust strategies with each new insight into the problem. Outside support from ex-Galileo consultants was limited to data analysis, flight software code changes, testbed simulations, and review of the safeguard and flight software patch commands.

6.2 Early Planning

In contrast to the prime mission for which the science and sequencing teams had several years to plan the orbital tour, and had sequences built for seven encounters before arriving at Jupiter, the GEM flight team had less than a year to prepare for the Europa mission and very little opportunity to pre-plan sequences. Taking advantage of flight and sequence development experience, the GEM planners, comprised of prime mission personnel, produced a highly focused Orbit Planning Guide to lay the groundwork for each orbit's science observations. Using clearly defined science objectives for each phase of GEM, the Project Science Group, supported by the Science Planning and Operations Team, generated a high level plan of specific observations allocated to each flyby. Based on available tape space, downlink resources, and preferred viewing geometries, some trades were made between mission phases to assure that the top priority science was achieved. In a two-week period following completion of the high-level plan, science coordinators and integrators defined each observation in terms of the target, tape recorder needs, bits to ground for both real-time science and playback, execution time, and priority. From these inputs, an Orbit Planning Guide containing an integrated time-ordered listing, a tape map, and an accounting of resource usage was generated. Concurrent with this activity, cruise activities for spacecraft and instrument maintenance along with a limited set of science observations were defined and a template of cruise activities built. These two products form the strawman plan to begin sequence development in GEM.

6.3 Sequence Development Process

The process used to generate orbital sequence command files was shortened from the 12 weeks used in prime mission to 8 weeks in GEM. An eight week development cycle roughly consistent with the average orbital period of 54 days reduces overlapping orbital sequence development and still provides for a sufficient number of iterations to check and modify the command files. The first two weeks of the eight-week cycle consist of updating the early plans defined in the Orbit Planning Guide and cruise template to account for the final selected aim point and trajectory, negotiated DSN station allocations, revised strategies, and incorporation of new activities in response to anomalies. Two examples of the latter are safeguard commands added to spacecraft turns and maneuvers to prevent bogus gyro data from falsely tripping fault protection and the gyro performance tests used to track and calibrate gyro degradation. Using the aim point and trajectory, remote sensing observation targets and timing are finalized and timing of other geometric events, such as occultations, magnetospheric sheet or wake crossings, are determined and planned for. The DSN tracking profile is integral to planning the total science bits to ground and to scheduling spacecraft activities requiring monitoring.

After the initial update, sequence development is an iterative process of merging updated inputs from the science instrument coordinators, science resource integrators, and spacecraft subsystem engineers. This is followed by checking the integrated product for resource conflicts, violations of rules defining operational limitations of spacecraft hardware and software, and self-imposed rules to maximize mission return within the capabilities of the spacecraft, ground system, and flight team structures. Resources that are closely managed are downlink bits to ground, tape recorder tracks, and onboard sequencing memory and processor time. Conservation of consumables with specified lifetimes is considered in planning but tracking planned versus actual usage is not done in GEM.

The iterative generation process begins with the delivery to a sequence integration engineer of electronic files containing all parameters needed by SEQGEN, a sequence generation software tool to expand each spacecraft activity into a set of mnemonic commands. Individual files from the science instrument teams, DMS tape integrator, real-time science integrator, and the Spacecraft and Sequence Team are first merged, put in time-order and checked for completeness, valid parameter definitions, and internal consistency before being expanded to the command level. There are two steps to the expansion process. First, SEQGEN expands the input definition file to a time ordered listing of mnemonic commands. Second, it models command execution on the spacecraft and checks the resultant response for constraint violations and resource claim conflicts. Diagnostic messages are reviewed by the integration engineers and, if necessary, assigned to the responsible instrument or subsystem representative for resolution. The mnemonic commands output by SEQGEN are translated into binary and packaged into command messages by SEQTRAN, the sequence translator, for radiation to Galileo. The merged activity definition file, the mnemonic command file, the expanded command file including the modeled commands, the diagnostics, and the command message file are released for constraint checking and validation. Errors and conflicts are resolved, corrected in the input files and the process begins again. Each orbital sequence goes through this process at least four times.

The encounter and cruise sequences are both developed in the same eight-week cycle but by different squads and with different levels of involvement by science planners. All instruments and subsystems are involved in generating and checking each encounter sequence; cruise sequences are generated almost entirely within the Spacecraft and Sequence Team. Science inputs to the cruise sequence are planned and implemented by a science systems engineer based on requirements supplied by the science teams and the resultant sequence is constraint checked by the instrument representatives twice in the development cycle. The Navigation Team and the Mission Control Team support both encounter and cruise sequence development.

6.4 Mini-Sequences and Real-time Commands

Mini-sequences are used for activities that are limited in scope and whose parameters cannot be defined months in advance. Typically generated in a day to a week, and executed in a reserved box in CDS active memory, they are used only for maneuvers in standard operations but become the main vehicles providing the flexibility required during anomaly investigation and recovery. Early in the gyro anomaly, spacecraft attitude updates which rely on inertial reference for the turn to execute correctly were removed from the stored sequences to provide time for investigation into the problem, to reduce the risk of a spacecraft fault during the turn, and to provide the opportunity to modify how the turns are commanded. In the event ongoing investigations determined the gyro-based turns to be unsafe, this strategy eliminated the need to cancel the background sequence to prevent their execution. Gyro performance tests and calibrations were also done as mini-sequences until their design stabilized enough to be included in the stored sequences. In the first seven months of GEM, thirteen anomaly related mini-sequences were generated compared to ten total in the year and a half of prime mission from G1 through E11. The ability of the reduced staff to accomplish this unplanned work load was largely the result of retaining experienced personnel and merging the engineering and sequencing teams. Co-location and enhanced flexibility in delivery schedules allow faster command file generation.

In addition to mini-sequences, real-time commands are used to supplement orbital sequences. These consist of individual commands to be executed either immediately upon receipt by the command decoder or at a specified later time. In standard operations, real-time commands are typically used to reset the command loss timer, to modify instrument operating modes, and to update flight software parameters. In the event of an anomaly, they are used for immediate response to ensure spacecraft safety, to read out data buffers for investigation, and to control the playback process to prevent loss of science data if a tracking station cannot support Galileo as planned. Complex real-time command packages are also used for flight software patches. Real-time commands are defined by system or subsystem engineers and, depending on their number and the complexity of their interaction, are generated by either the Mission Control Team or the Spacecraft and Sequence Team.

6.5 Playback Tables

The playback of recorded data continues in GEM in a similar manner to that of the Galileo Prime Mission. Two passes through the tape in each orbit is standard, with the goal of maximizing science data return while limiting the inefficiency inherent in the process. Inefficiency is created in two ways; by slewing between observations to be played back, and by processing data too slowly to keep up with higher data rates. The former is somewhat predictable, and is accounted for by retaining a 4% inefficiency margin prior to developing the playback plan. As the playback progresses and the slewing inefficiencies are tracked, any excess margin being retained is released back to the science teams. Typical inefficiency amounts in GEM have been between 2 and 4 megabits per orbit. In order to reduce slewing inefficiency in each orbit, the playback coordinator evaluates which data are selected for playback in which pass. Observations are often previewed in the first pass and then optimized in the second pass by adjusting spatial coverage or compression. Large observations (using greater than 500 tape tics) are usually split evenly between passes to reduce the amount of tape crossed without stopping to play back data. The second cause of inefficiency is slow processing rates of certain data types on-board the spacecraft. If the downlink rate is high (generally 120 bits per second or higher), the process of reading data from the tape, performing onboard processing and compression, and creating completed packets for downlink can take longer than it takes to drain the Multi-Use Buffer (MUB) of packetized data. This results in the receipt of PWS Fill data until enough data have been read off the tape to form completed packets and VCDUs for downlink. This type of inefficiency is not quantifiable, but can be minimized by playing back multiple data types together (ride-along data), increasing the effective rate at which data is packetized and sent to the ground.

The playback process is controlled by a Playback Table consisting of instructions for selecting the data to be returned and the compression factors to be applied by the onboard data processors. The table is divided into segments which are uplinked as needed thereby allowing weekly modifications to the data return plan to account for data compression uncertainties, for the inefficiencies discussed above, and for replay of data lost on the first pass due to any gaps in data receipt on the ground.

The playback plan is developed in parallel with the orbital sequence development, and is updated on a weekly basis to allow changes based on increased or decreased capability and compression performance. The Science Planning and Operations Team Chief retains a margin of 2 megabits in each orbit to protect the return of the last observation on the tape. As the process nears the end of the second pass through the tape, some portion of margin may be released to the science teams based on remaining uncertainties in observations to be played back, and on the potential science return to be gained by using the retained margin capability. At the very last weekly update to the playback table, the team at the end of playback will generally select extra data in case compression might be better than expected in the observations still to be returned, thereby utilizing any unused playback capability and optimizing the science return for the orbit. The playback process is not very different for GEM than in the Galileo Prime Mission, but with shorter encounter periods, less observations recorded on the tape, and playback starting within the encounter sequences in some orbits, the process is quicker and more refined, and the data return is maximized.

7. Summary of Encounters in the Past Year

7.1 Europa 11

The last of the ten satellite encounters in the Galileo prime mission and the third flyby of Europa in the Galileo Mission, Europa 11, occurred on November 6, 1997, at a closest approach altitude of 2,042 km at 20:32 GMT. The encounter sequence was 7 days long and began on November 2, 1997, 16:00 GMT and lasted until November 9, 1997, 16:00 GMT. The end of the encounter sequence represented the end of the second magnetosphere survey "mini-tour". This second "mini-tour" provided continuous magnetospheric survey coverage since the beginning of the G7 cruise period. Figure 4 shows the region during the E11 encounter where continuous coverage was achieved. No RTS (real-time science) data was collected during the cruise phase of this orbit. This encounter contained the longest recording of magnetospheric data around Europa closest approach of the entire tour. The length of the recording was 2 hours and 40 minutes, and was the best opportunity to study the 'far' regions of Europa and the Io plasma torus. This recording also encompassed the Jovian magnetic equator crossing. The E11 encounter sequence was the first orbit to use the new rules of tape recorder operations that were planned to be used in the GEM. The primary difference between these and the prime mission rules are: 1) the amount of wait time required between recorded events on reverse running tracks,

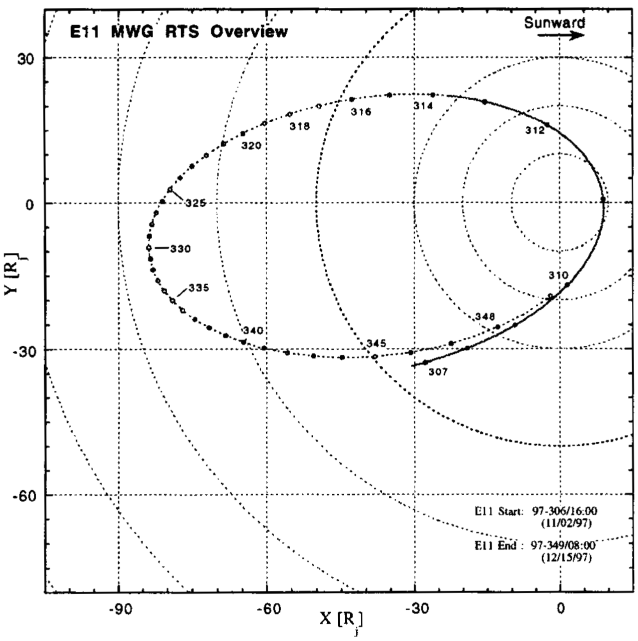

Figure 4. E11 MWG RTS Overview

2) use of track changes going from forward running tracks to reverse running tracks, and 3) the amount of margin reserved at the end of each track. In the old rules, the wait times were 4 minutes, versus 1 minute for the GEM rules. The use of track change commands to transition between forward running and reverse running tracks reduced the time of the transition from about 10 minutes down to about 1 minute. These changes were deemed necessary due to the nature of the GEM observations. In GEM, an extensive amount of tape resources are expended on Europa. Reducing the wait and track transition times permit more high-resolution images to be taken of Europa than in the prime mission. The new rules were implemented in the E11 plan and the recorded observations all executed nominally on the spacecraft. The primary science objectives of this orbit were remote sensing observations of the surface of Europa, observations of features within Jupiter's atmosphere, including a brown barge, the northern auroral zone, and an extensive lightning detection campaign. Another objective on this orbit was to achieve the highest resolution images to date on four of Jupiter's small inner satellites: Thebe, Metis, Amalthea, Adrastea. The resolutions ranged from 4.8 to 8.6 km/pixel and were the most comprehensive set of observations of these satellites taken in the tour. An Earth occultation by Jupiter provided the radio science experiment with unique northern mid-latitude 'views' of the structure of Jupiter's atmosphere. The Europa features of interest for this flyby consisted of observations of ejecta material from the Pwyll crater, wedge-shaped ("pull apart") dark bands, near-terminator coverage of mottled terrain, the relatively fresh Mannann'an crater, and another area of Europa that was previously unexplored. Figure 5a shows the Europa encounter geometry and observations within ±1 hour of closest approach. Figure 5b shows a north pole trajectory plot of the encounter period with the key science observations highlighted. One set of spacecraft turns was required for atmospheric feature track observations, Io observations, and ring observations. These science observations began about 12 hours after the perijove passage, when the spacecraft moved to a position such that the instruments' line-of-sight to the targets was obscured by the spacecraft booms. To get an unobscured view of these targets, the spacecraft was turned about 36 degrees. The spacecraft was kept at the turned attitude for about 1.5 days, which permitted observations of Jupiter and Io at several different phase angles (angle between the sun, Jupiter, and the spacecraft). At the completion of the E11 playback, the Galileo spacecraft had returned about 2.1 Gbits of data throughout the prime mission and 1,645 images of Jupiter, its satellites, and the ring system (where an "image" corresponds to one shuttered scene).

7.2 Europa 12

The next encounter was also with Europa and signified the start of the GEM. This encounter was Galileo's closest ever encounter with Europa. The encounter occurred on

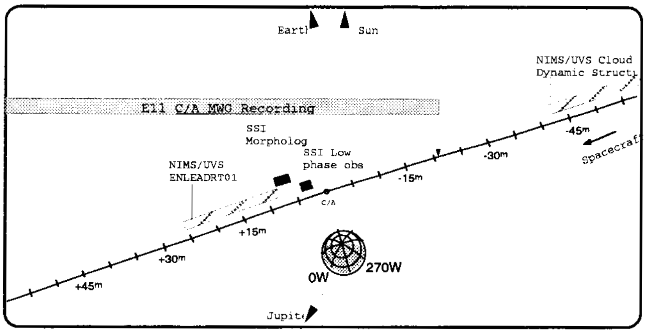

Figure 5a. Europa—Orbit 11 Flyby Geometry

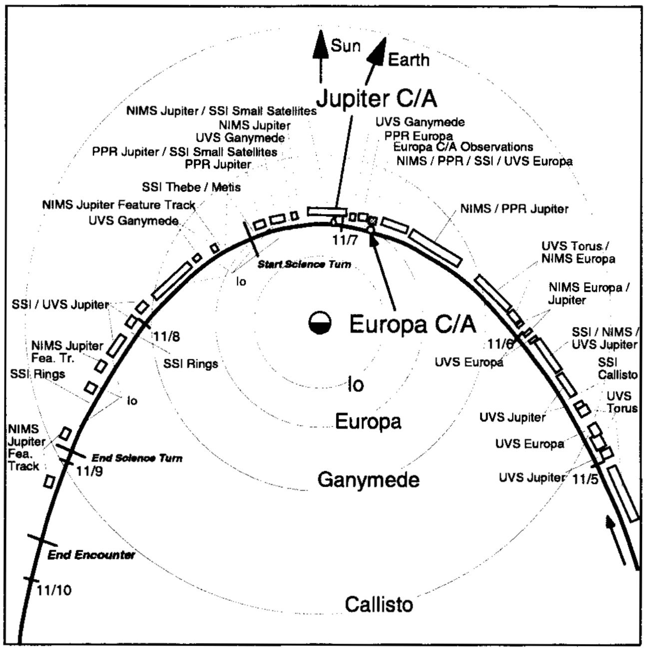

Figure 5b. Europa—Orbit 11 Encounter Trajectory

December 16, 1997, at an altitude of 200 km at 12:03 GMT. The primary differences between a GEM encounter and one during the Galileo prime mission is the scientific focus. As a result of the more highly focused objectives and the reduced resources available to generate the sequences, the Europa encounter sequences are much shorter than in the prime mission, typically about 2 days instead of 7 days. In addition, a large amount of the spacecraft resources (tape and bits-to-ground) are expended on the prime target, in this case Europa. In the prime mission, satellite observations of Europa would typically have to compete for resources among many other science objectives, including Jupiter atmospheric observations, other satellite observations, etc. During the Europa encounters in GEM, Europa objectives and observations typically get the bulk of the spacecraft resources. For example, Europa science objectives get about 82% of the available bits-to-ground for all these orbits.

The E12 encounter sequence started on December 15, 08:00 GMT, and ran until December 17, 18:00 GMT. The E12 orbit provided the first of three nontargeted encounters that occur in GEM. (See ref. 1 for a definition of nontargeted encounters.) The E12 nontargeted encounter was with Ganymede at an altitude of 14,389 km. The geometry of this flyby was unique in that a single 4-frame Solid State Imaging (SSI) observation could be taken of Ganymede's Gilgamesh Basin. Gilgamesh is interpreted to be the youngest large impact basin on Ganymede. This observation will be used to better constrain the surface ages of Ganymede with possible extrapolation to Europa. The close flyby geometry of Europa offered by this orbit provided unique opportunities for science data acquisition. For the remote sensing instruments, the primary features of interest on Europa included the Conamara ice raft region, which was originally discovered in the E6 orbit, the Pwyll crater region, mottled terrain, and the wedge-shaped band area imaged in C3. Some of the images acquired on this orbit were planned as stereo pairs. Stereo imaging is a technique which is used to discern the topography of a region by viewing that region at different geometries (i.e., look angles). In particular, the Pwyll crater and wedge-shaped band region observations were taken in stereo. Because of the close flyby on this orbit, the highest resolution images of Europa of the entire Galileo tour where acquired. The highest-resolution was 6m/pixel of the mottled terrain region of Europa. These data will be key in assessing the small-scale processes associated with this region, its formation and modification. Figure 6a shows the encounter geometry and observations that taken within ±1 hour of Europa closest approach. The plot also shows the period of time for the high-time resolution recording by the fields and particles instruments. Figure 3b shows a north pole view of the orbit trajectory for the two day encounter sequence with the key science observations highlighted. In addition to remote sensing, there were radio science and magnetospheric science objectives during this encounter with Europa. Again, because of the unique flyby altitude, radio science acquired two-way coherent tracking data for 20 hours around closest approach for the purpose of better determining Europa's gravity field and to probe the internal structure of Europa. Magnetospheric science observations in the orbit consisted of about two days of real-time science data collection at the minimum collection rate of 20 bps, and high-time resolution recording during the period of closest approach to Europa. This was particularly important on E12 because of the close flyby to further confirm whether

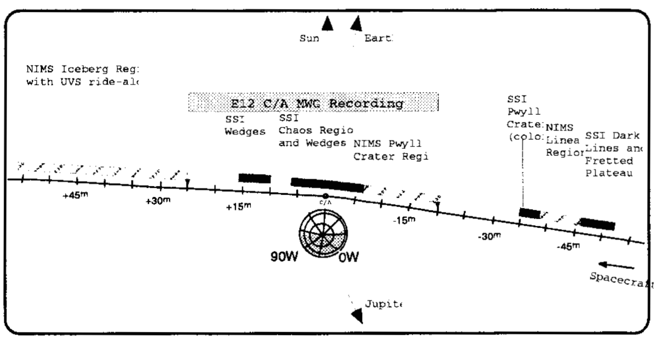

Figure 6a. Europa—Orbit 12 Flyby Geometry

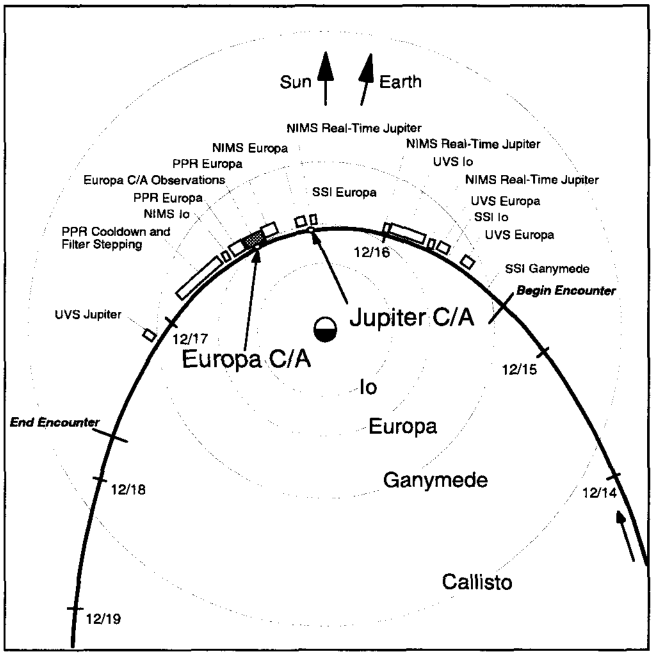

Figure 6b. Europa—Orbit 12 Encounter Trajectory

or not Europa has its own intrinsic magnetic field. For the RTS data collection generally all fields and particles instrument participate. In E12, prior to perijove, there was an AACS gyro anomaly (see Section 4.2) that disabled the onboard software data compression algorithm which is used to process the real-time Plasma Wave Subsystem (PWS) data. The PWS instrument measures plasma wave and radio emission phenomena in the magnetosphere of Jupiter. Therefore, the collection of PWS real-time data ceased immediately following the anomaly and remained off throughout the encounter period. Fortunately, this anomaly did not affect the PWS data collection during the magnetospheric recording near Europa closest approach. In GEM, no attempt was made to make the magnetospheric science survey continuous throughout the orbit. The primary reasons for this were: 1) the scientific focus in GEM is on Europa and the Io plasma torus (inner magnetosphere), and 2) near continuous DSN tracking coverage throughout the orbit as in the prime mission was not feasible in the extended mission due to other planetary missions having higher priority for DSN tracking coverage. Therefore, the magnetospheric survey is concentrated in the few days around Europa closest approach. Figure 7 shows the periods of time RTS survey data was collected in the GEM orbits E12 through E16. Other observations in the E12 orbit included Io monitoring observations at visible, infrared, and ultraviolet wavelengths and four observations of Jupiter at infrared and ultraviolet wavelengths. One unique instrument engineering event in this orbit involved cooling down the Photopolarimeter/Radiometer (PPR) instrument in order to step its filter wheel beyond the previous stuck position.[1] This activity was successful and will enable PPR to continue with its science objectives for the remainder of GEM. The return of the science data acquired during this encounter was originally planned to start in the encounter sequence. However, due to the gyro anomaly that occurred prior to perijove, the data compression algorithm was disabled by the spacecraft and playback did not commence until after ground intervention . As a result of this anomaly and the subsequent gyro anomaly that occurred during the Europa C/A+3 day OTM, significant hits to the telecommunication capability in this orbit resulted. The original planned science downlink capability for this orbit was 123 MBTG. Because of the various gyro anomalies, the actual science downlink capability acquired for E12 was 80 MBTG. Fortunately, late changes to the science data playback plan returned most of the highest priority science in this orbit, including the highest-resolution images of Europa and the high-time resolution magnetospheric data around Europa closest approach.

7.3 Europa 13

The second Europa encounter in GEM occurred on February 10, 17:57 GMT, at an altitude of 3,562 km. For this encounter there was no remote sensing or magnetospheric data collected because Earth and Jupiter were in solar conjunction around two weeks after perijove on that orbit. The solar conjunction period lasted about 19 days. As a result, there was very little telemetry capability available to return any science data collected during the encounter period. It was decided that a better use of the very limited telemetry capability in E13 was to continue returning Europa 12 data through the E13 cruise period. One science objective that was accommodated during the E13 encounter was the collection of radio science data around closest approach. The objective was to perform gravity field measurements of Europa, thus probing its internal structure. This was accomplished with two-way coherent tracking data throughout the encounter period. Once the solar occultation period ended, playback of E12 science

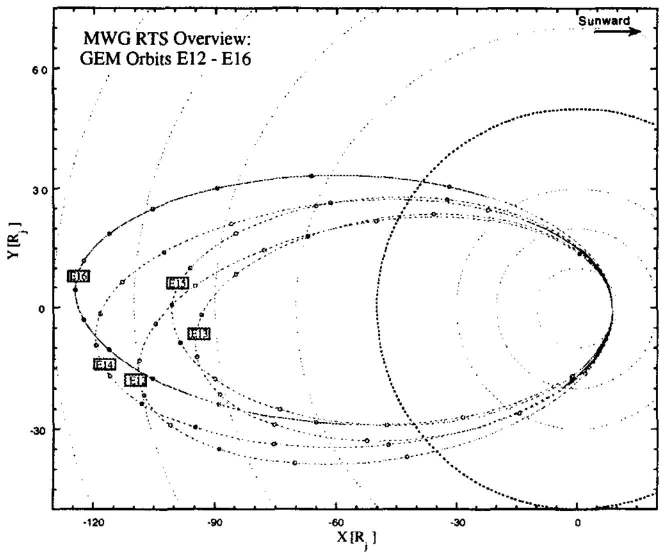

Figure 7. MWG RTS Overview—E12-E16

data continued until just prior to the start of the E14 encounter sequence, until March 27.

7.4 Europa 14

The next encounter with Europa occurred on March 28, 1998, at an altitude of 1,645 km at 13:21 GMT. The E14 encounter sequence started on March 27, 13:00 GMT, and ended on March 31, 02:15 GMT. The encounter geometry in this orbit was very similar to that of E12, except in the altitude of the flyby and the viewable hemisphere of Europa at the time of closest approach. This offered views of different types of terrain on Europa than did the E12 encounter. The primary Europa science objectives for this orbit included high-resolution observations of various terrain types to understand composition, i.e., determining the non-ice components, geologic formation and modification, characterization of the geologic units and global stratigraphy. The terrain types of interest on this flyby included Mannann'an crater, Tyre Macula (i.e, dark spot), triple bands, bright plains, ice rafts, and wedge regions. Stereo imaging of the Mannann'an crater and the dark spot region was acquired to provide topographic information about these features. The details of the geometry and observations in the E14 encounter period are shown in Figures 8a and 8b. Magnetospheric science observations in this period included about four days of RTS collection at 20 bps and high-time resolution recording around Europa closest approach. The low rate, real-time science data collection performed in each perijove pass was obtained to provide background and contextual data for the recorded high-rate measurements at closest approach. For the high-time resolution recorded data, the *in situ* instruments make measurements of the magnetic fields and particle interactions within the region, including waves and radio signals. These measurements collectively contribute to the understanding of particle pickup processes near Europa, and thermal and non-thermal plasma interactions in this region. Playback of the E14 science data was delayed until the acquisition of an infrared wavelength observation of Callisto very late in the encounter period. The closest approach to Callisto on this orbit was about 1,200,000 km; however, it provided a unique view of the trailing hemisphere of Callisto. Observations made during the Galileo prime mission, Voyager, and the International Ultraviolet Explorer (IUE) spacecraft have shown that there are compositional differences between the leading and trailing hemispheres of Callisto. The term leading and trailing hemisphere refers to the side of Callisto relative to its orbital motion around Jupiter. Callisto is in synchronous rotation with Jupiter, i.e. it rotates on its axis in the same time as it revolves around Jupiter. Therefore, the same hemisphere of Callisto "faces" its orbital path around Jupiter. The leading side is the side of Callisto in the direction of orbital motion and the trailing side is the side opposite that motion. This observation, in conjunction with one that will be acquired of the trailing side on the Callisto 20 orbit, is intended to address some of these compositional differences.

Other satellite science objectives in the orbit included Europa gravity field measurements, Ganymede global-scale imaging to provide data on the radius, shape, color, photometry, and mobility of surface frosts, and extensive Io monitoring, from ultraviolet to thermal (far infrared) wavelengths, one Jupiter aurora observation, and an ultraviolet and extreme-ultraviolet observation of the Io plasma torus. The observations of Io are of particular importance on this orbit. The closest approach to Io in the orbit was about 250,000 km. This relatively close pass, combined with the orbital geometry, provided the best resolution to date of the north and south polar regions of Io. This multicolor imaging observation achieved a resolution of 3 km/pixel (the best color coverage in the prime mission was 10 km/pixel).

Playback of the E14 science data began on March 31 and proceeded nominally throughout much of the cruise period. Two days prior to the end of playback, another AACS anomaly occurred during OTM-47 that resulted in spacecraft safing, which terminated playback. Fortunately, the second pass through the tape recorder had already completed and an extra

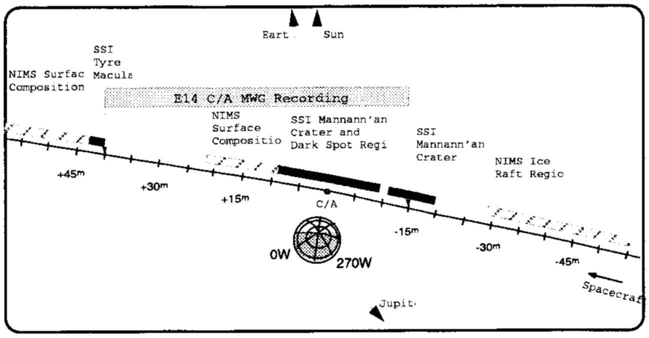

Figure 8a. Europa—Orbit 14 Flyby Geometry

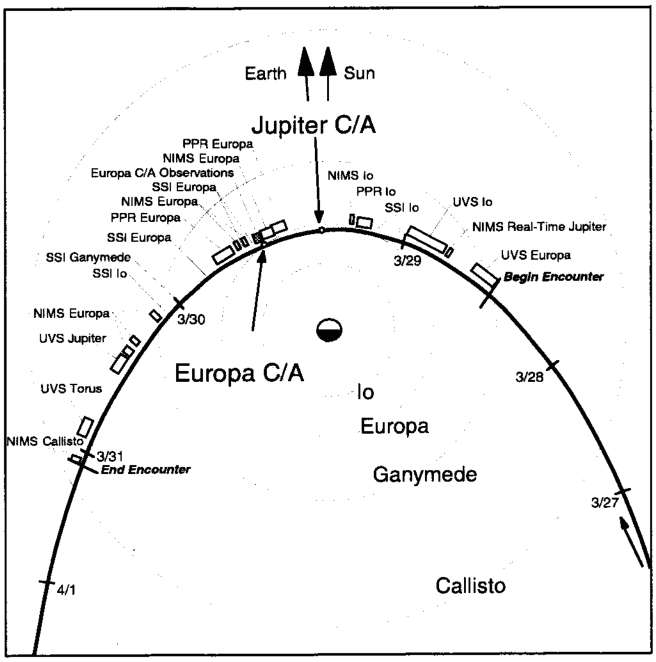

Figure 8b. Europa—Orbit 14 Encounter Trajectory

third pass through had started when the anomaly occurred.

7.5 Europa 15

The fourth Europa encounter in GEM occurred on May 31, 21:12 GMT, at an altitude of 2,515 km. This encounter was the second inbound (pre-perijove) encounter (E13 was the first) with Europa in GEM, and the first inbound encounter to perform remote sensing and magnetospheric observations, thus providing some unique viewing geometry of Europa. The primary science objectives on this orbit were high-resolution observations of different features on Europa, distant global compositional mapping of Europa, recording of fields and particles data during the Europa closest approach, gravity field measurements of Europa, extensive Io surface monitoring observations, including Io eclipse observations and plume monitoring, ultraviolet and extreme ultraviolet observations of the Io plasma torus, and Jupiter NIMS and UVS observations acquired in real time. The encounter sequence was just over three and a half days long, began on May 30, 21:00 GMT, and ended on June 3, 10:00 GMT. The magnetospheric RTS data collection during the encounter occurred at the minimum downlink rate of 20 bps with a brief 6 hour period at 40 bps around Europa closest approach. The Europa features examined on this orbit included stereo and color imaging of the Cilix massif, which is believed to be the largest massif (i.e., mound or mountain) on Europa, stereo imaging of the region east of Tyre Macula, and near-terminator regional maps of unexplored mottled terrain. Near terminator observations are of particular importance for deriving topography of the region. Because of the low sun angles for these observations, shadows cast by the uneven terrain are distinct and measurable. Therefore, heights of mounds, ridges, or ice rafts can be determined.

Extensive Io surface monitoring observations were acquired on this orbit with all the remote sensing instruments. One of the SSI Io surface monitoring observations on this orbit failed to execute due to an AACS anomaly that occurred while targeting to Io for this observation. Four Io eclipse observations were taken with SSI when Io was in Jupiter's shadow. These eclipse images have proven to be the best way to discover and monitor lava temperatures and magnetospheric interactions with plumes and Io's atmosphere. The eclipse observations on this orbit were taken in pairs; one observation occurred at the start of the eclipse and the other at the mid-point. The purpose of this observation strategy was to look for any short-term variations of Io while in the shadow of Jupiter. An Io plume monitoring observation of the Kanehekili plume was also performed on this orbit. Observations of volcanic plumes are timed such that the plume is expected to be on the limb of Io. This allows for better identification and characterization of the plume against a dark sky. Plume heights, for example, can be easily determined using this technique. The details of the orbit geometry and observations contained in the E15 encounter period are shown in Figures 9a and 9b. Interesting results were obtained on this encounter; in fact, it was discovered that the Cilix massif is not a massif at all but rather an impact crater.

7.6 Europa 16

During the execution of the E16 encounter sequence, about 7 hours before Jupiter closest approach and 12 hours before Europa closest approach, the spacecraft experienced a despun bus reset event that resulted in spacecraft safing and termination of the science sequence (see Section 3.3). This was the first encounter sequence missed by Galileo during all

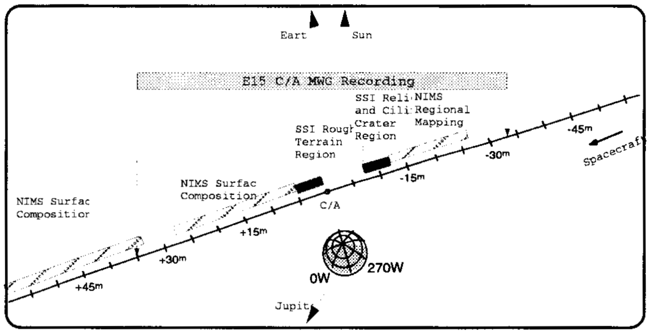

Figure 9a. Europa—Orbit 15 Flyby Geometry

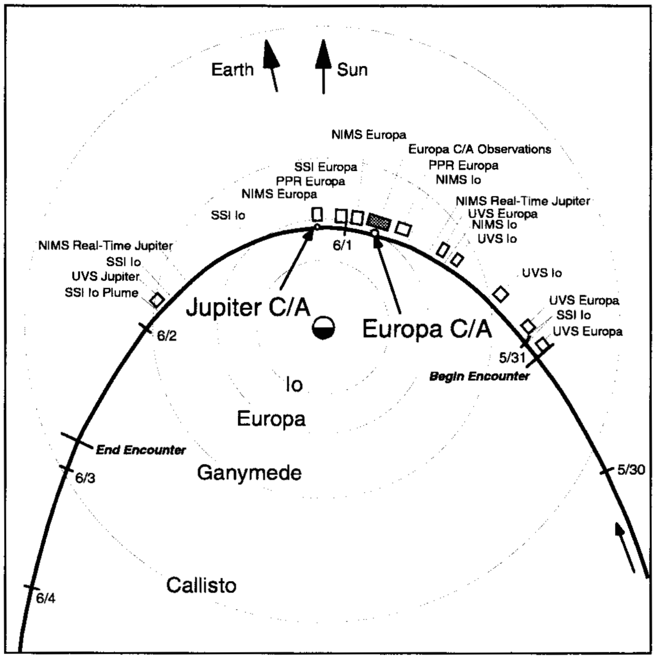

Figure 9b. Europa—Orbit 15 Encounter Trajectory

of its orbital operations to date. This loss was particularly painful due to the large downlink capability on this orbit and the first extensive atmospheric observations in GEM. Prior to sequence termination, however, some science data was recorded of Io and Jupiter using the NIMS and PPR instruments. Subsequent to the bus reset, the spacecraft was reconfigured back to its normal state to initiate playback of this data. However, before starting to play back this data, an extensive detector calibration of the NIMS instrument was recorded on the tape. This data along with the other E16 data on the tape were the first data played back during the cruise period of E16.

In addition to the E16 data, the revised playback plans consisted of returning a considerable amount of E15 data that had not been returned previously. Typically, the science sequences record much more data than can be returned during the cruise period of a given orbit. Therefore, there still remained on the tape recorder E15 data that had not been played back. In addition, it was decided to configure the fields and particles instruments for the collection of RTS data during the cruise period. It turns out that this orbit traverses the dusk magnetosphere region similar to that of the C9 orbit. This RTS data will be extremely useful in providing cross-correlation with C9 to further understand the magnetospheric processes that occur in this region. The RTS data collection continued through Jupiter apoapsis on this orbit in a region of the magnetosphere yet unexplored by Galileo. So while the loss of nearly all the E16 encounter science data was a considerable disappointment, the downlink capability of this orbit was still able to be utilized very effectively to acquire further Jupiter science data.

8. New Scientific Discoveries

New scientific discoveries have continued to be made from the Galileo data over the past year, both from further analysis of the data returned in the prime mission as well as the more recent data returned from the GEM. Some of the more salient of these reported recently by the science teams relate mostly to new results related to the Galilean satellites. There is now even further evidence from photographs for Europa's surface being geologically very young, with some estimates being as little as a few million years, and the probable existence of a liquid layer below its ice crust. It has been conclusively established that there are very high temperature volcanic eruptions on Io, suggesting a very magnesium rich composition for the lavas. Two independent instruments have shown temperatures of at least 1700K, and perhaps as high as 2000K, well above the hottest eruptions on Earth today. Positive identification of a number of non-water ice constituents has been made on Callisto and Ganymede, including CO_2 and SO_2, as well as carbon-hydrogen and carbon-nitrogen compounds, some as gas inclusions in the surface materials. A tentative identification of magnesium and sodium salts (sulfates and carbonates) has been made on the surface of Europa. This is particularly significant because the most likely source of such salts would be from a briny ocean below the ice. Carbonated water is a candidate explanation for the generation of enough pressure to explain the apparent sprays of debris seen on the surface. One very significant discovery resulting from the study of data from Galileo's magnetometer is that Europa and Callisto may be interacting with the Jovian magnetic field as if they were conducting shells, implying a high conductivity layer such as a salty ocean within ~100 km of the surface. For Europa, this is a strong indication of the presence of a liquid ocean beneath the icy surface today. Photographic studies of the surface only indicate that there has been such a body of liquid at some time in the past, but not necessarily at present. This result for Callisto is also significant in its own right, but even further piques the interests of the scientific community because of the implications it has for current models of Callisto, also based on Galileo data, which show a relatively undifferentiated interior for the satellite.

A significant non-satellite result is the acquisition of the highest ever resolution pictures of Jupiter's aurora in a campaign which was coordinated with ground and Hubble Space Telescope observations to study a wide range of magnetosphere-atmosphere interactions. Preliminary analyses indicate that the visible auroras seen in Galileo images are lower in the atmosphere than predicted, and atmospheric scientists now are developing new theoretical models to explain the auroral data from all the different sources.

9. Acknowledgments

The success of Project Galileo is due to the efforts of a large number of people, all of whom deserve acknowledgment for their contributions. Special recognition is due the members of the GEM Team who have kept this tremendous success going despite significantly reduced resources and some extra challenges in operating the spacecraft.

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10. References

1. O'Neil. W.J., et al., "Project Galileo Completing Its Primary Mission, paper IAF-97-Q.2.02, presented at the 48th Congress of the International Astronautical Federation, Turin, Italy.

2. McEwen, et al., High-Temperature Silicate Volcanism on Jupiter's Moon Io, Science, 3 July 1998.

A View From The Galileo Orbiter—

Selected Images Of Io And Europa

Close-up Color View of Io

This is the highest resolution color picture taken so far of Jupiter's volcanic moon Io. At 3 kilometers (about 2 miles) per picture element, the fiery satellite is seen against a backdrop of Jupiter's cloud tops, which appear blue in this false-color composite. Among the surprises seen on the moon's surface are several small, distinctly greenish patches and subtle violet hues at the cores and margins of bright sulfur dioxide-rich regions (like the one in the lower right). Dark spots, many flagged by bright red pyroclastic deposits (deposits from explosive ejecta), mark the sites of current volcanic activity. Most of Io's riotous color is due to the presence of sulfur compounds, but the dark materials that make up the flows and calderas are probably silicate rock.

P-49939

Europa "Ice Rafts"

This image of Jupiter's icy satellite Europa shows surface features such as domes and ridges, as well as a region of disrupted terrain including crustal plates which are thought to have broken apart and "rafted" into new positions. The image covers an area of Europa's surface about 250 by 200 kilometers and is centered at 10° north latitude, 271° west longitude. The color information allows the surface to be divided into three distinct spectral units. The bright white areas are ejecta rays from the relatively young crater Pwyll, which is located about 1,000 km to the south (bottom) of this image. These patchy deposits appear to be superposed on other areas of the surface, and thus are thought to be the youngest features present. Also visible are reddish areas which correspond to locations where non-ice components are present. This coloring can be seen along the ridges, in the region of disrupted terrain in the center of the image, and near the dome-like features where the surface may have been thermally altered. Thus, areas associated with internal geologic activity appear reddish. The third distinct color unit is bright blue, and corresponds to the relatively old icy plains.

P-49853

Active Volcanic Plumes on Io

This color composite image shows two volcanic plumes on Io. One plume was captured on the bright limb or edge of the moon (upper right inset), erupting over a caldera named Pillan Patera after a South American god of thunder, fire, and volcanoes. The plume seen by Galileo is 140 km high and was also detected by the Hubble Space Telescope. Galileo will pass almost directly over Pillan Patera in 1999 during the first Io encounters at a range of only 600 km.

The second plume, seen near the terminator, is called Promentheus after the Greek fire god (lower right inset). The shadow of the 75 km high airborne plume can be seen extending to the right of the eruption vent. The vent is near the center of the bright and dark rings. Plumes on Io have a blue color, so the plume shadow is reddish. The Promentheus plume can be seen in every Galileo image with the appropriate geometry, as well as every such Voyager image acquired in 1979. It is possible that this plume has been continuously active for more than 18 years. In contrast, a plume has never been at Pillan Patera prior to the recent Galileo and Hubble Space Telescope images.

P-48956

Europa—Ice Rafting View

This view of a small region of the thin, disrupted, ice crust in the Conamara region of Europa shows the interplay of surface color with ice structures. The white and blue colors outline areas that have been blanketed by a fine dust of ice particles ejected at the time of formation of the large (26 km in diameter) crater Pwyll some 1,000 km to the south. A few small craters of less than 500 meters in diameter can be seen associated with these regions. These were probably formed at the same time as the blanketing occured by large, intact, blocks of ice thrown up in the impact explosion that formed Pwyll. The unblanketed surface has a reddish brown color that has been painted by mineral contaminents carried and spread by water vapor released from below the crust when it was disrupted. The original color of the icy surface was probably a deep blue color seen in large areas elsewhere on the moon. The colors in this picture have been enhanced for visiblility.

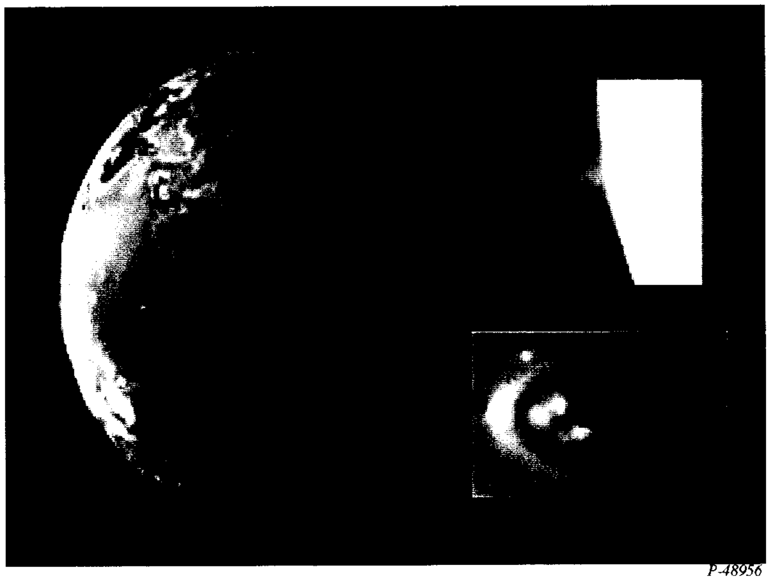
P-49434

Pwyll Impact Crater

This computer-generated perspective view of the Pwyll impact crater on Europa was created using images taken from different angles on the different orbits have been combined to generate a model of the topography of Pwyll and its surroundings. This simulated view is from the southwest at a 45° angle, with the vertical exaggerated four times the natural size. The colors represent different elevation levels with blue being the lowest and red the highest. Pwyll, about 26 km across, is unusual among craters in the solar system, because its floor is at about the same elevation as the surrounding terrain. Moreover, its central peak, standing approximately 600 meters above the floor, is much higher than its rim. This may indicate that the crater was modified shortly after its formation by the flow of underlying warm ice.

P-49637

P-49939



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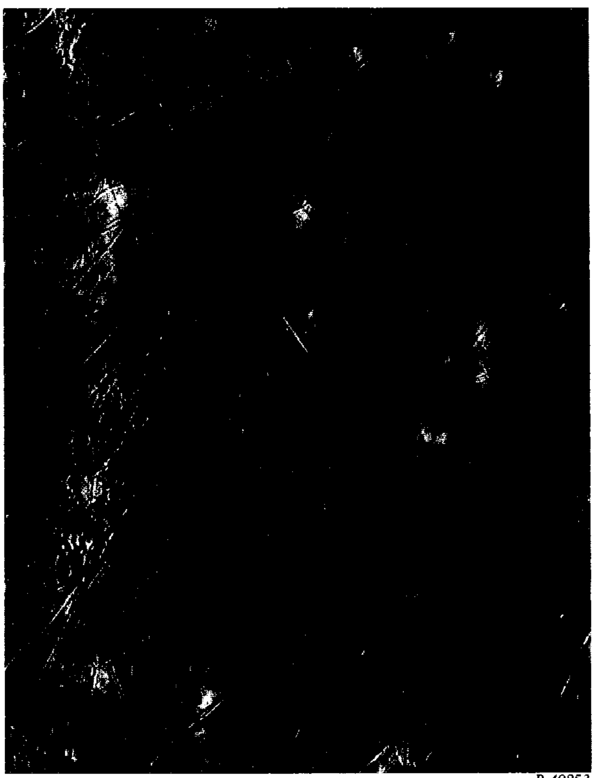

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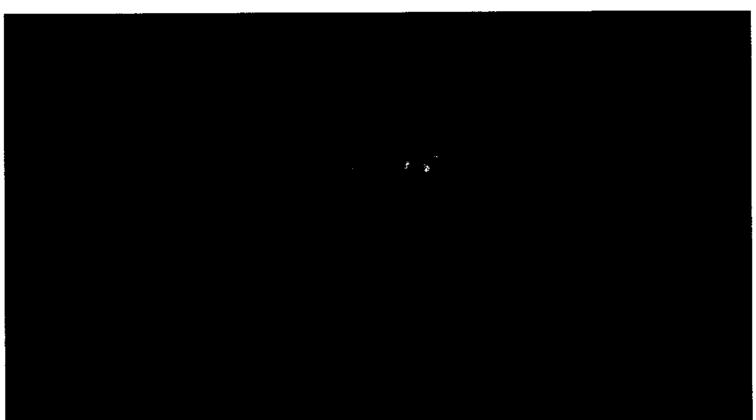

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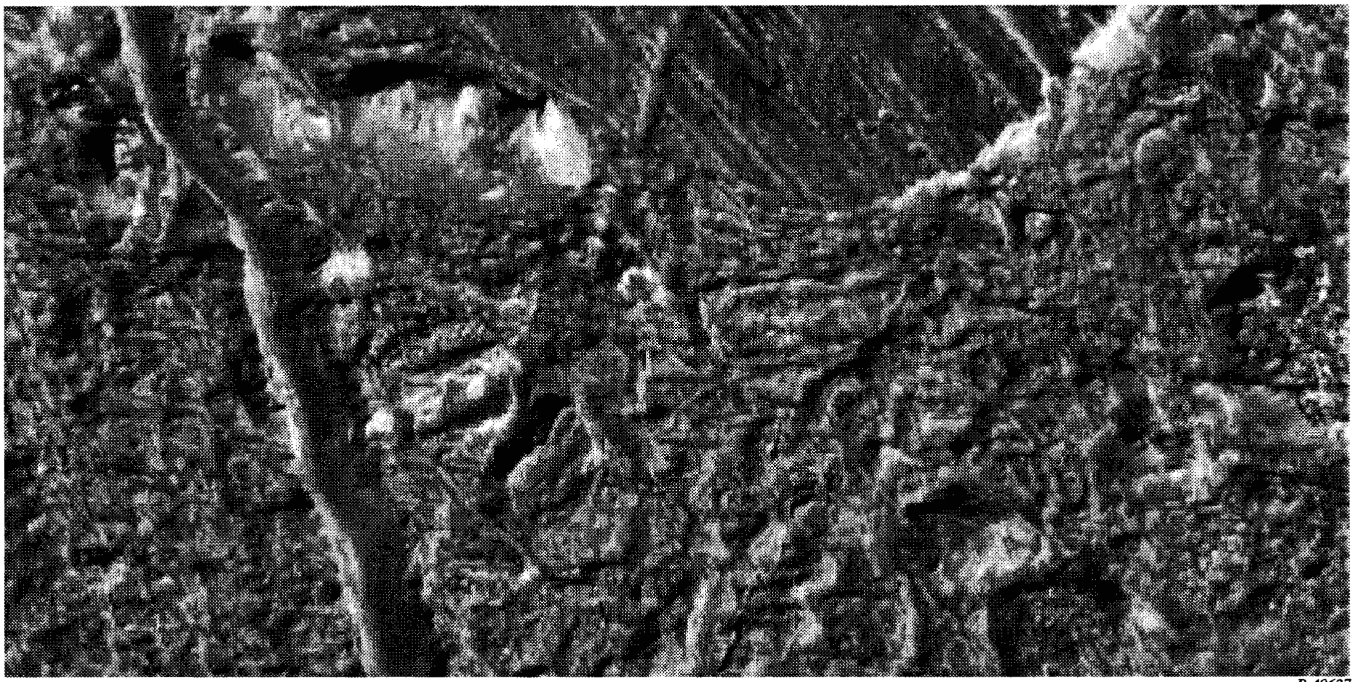
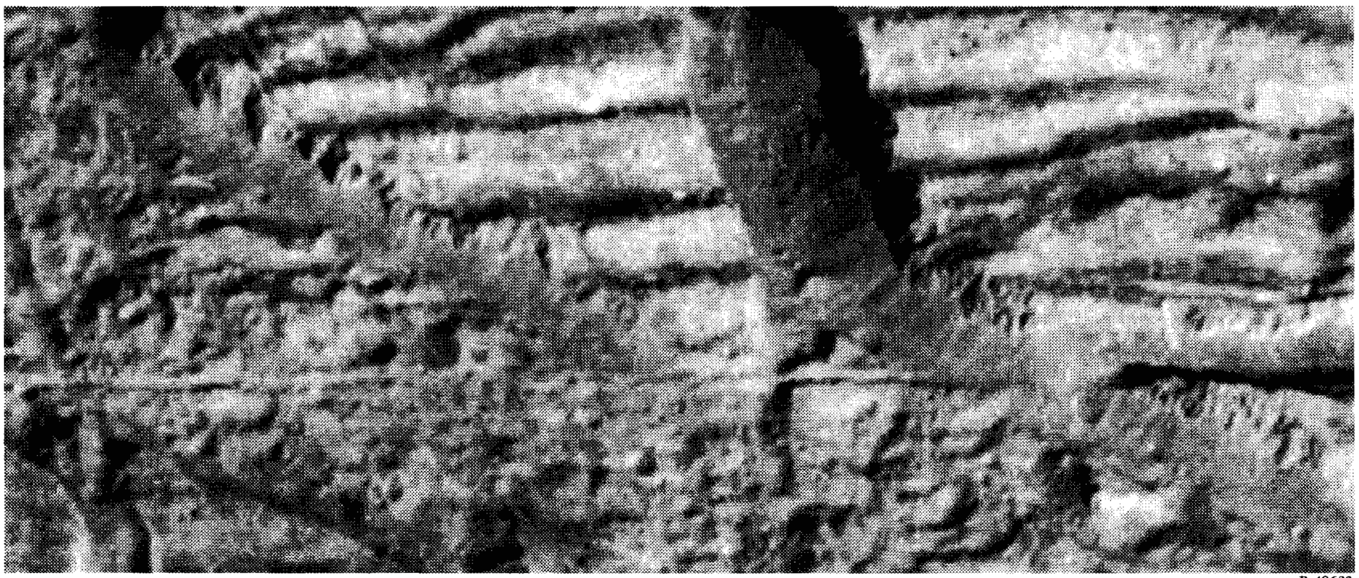


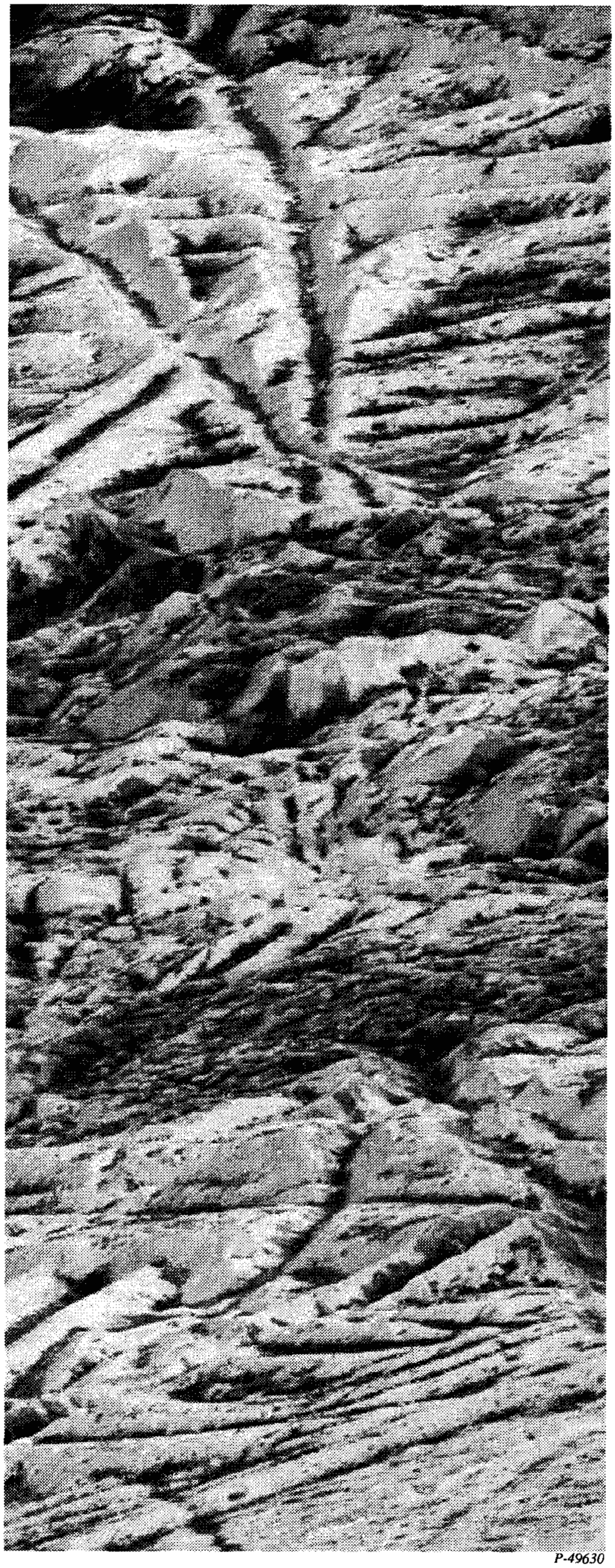
P-49627

The Conamara Chaos region on Jupiter's moon Europa consists of an area where the icy surface has been broken into many separate plates that have moved laterally and rotated. These plates are surrounded by a topographically lower material that may have been emplaced as water, slush, or warm flowing ice, which rose up from below the surface. One of the plates is seen here as a flat, lineated area in the upper portion of the image. Below this plate, a tall twin-peaked mountain of ice rises to a height of more than 250 meters. The surface in this area appears to consist of a jumble of many different sized chunks of ice. Though the surface may have consisted of a loose jumble of ice blocks while it was forming, the large fracture running vertically along the left side of the image shows that the surface later became a hardened crust, and is frozen today. The Brooklyn Bridge in New York City would be just large enough to span this fracture.



P-49632

This image shows a very high resolution view of the Conamara Chaos region on Europa. It shows an area where icy plates have been broken apart and moved around laterally. The top of this image is dominated by corrugated plateaus ending in icy cliffs over a hundred meters high. Debris piled at the base of the cliffs can be resolved down to blocks the size of a house. A fracture that runs horizontally across and just below the center of the Europa image is about the width of a freeway.



P-49630

◀ Highest Resolution Image of Europa

During its twelfth orbit around Jupiter, Galileo made its closest pass ever of Jupiter's icy moon Europa, souring 200 kilometers above the icy surface. This image was taken near the closest approach point, at a range of 560 kilometers, and is the highest resolution picture of Europa that will be obtained by Galileo. The image was taken at a highly oblique angle, providing a vantage point similar to that of someone looking out an airplane window. The features at the bottom of the image are much closer to the view than those at the top of the image. Many bright ridges are seen in the picture, with dark material in the low-lying valleys. In the center of the image, the regular ridges and valleys give way to a darker region of jumbled hills, which may be one of the many dark pits observed on the surface of Europa. Smaller dark, circular features seen here are probably impact craters.

P-49629

▲ Dark and Bright Ridges on Europa

This high-resolution image of Europa, whose dark, relatively smooth region at the lower right hand corner of the image which may be a place where warm ice has welled up from below. The region is approximately 30 square kilometers in area. An isolated bright hill stands within it. The image also shows two prominent ridges which have different characteristics; youngest ridge runs from left to top right and is about 5 kilometers in width (about 3.1 miles). The ridge has two bright, raised rims and a central valley. The rims of the ridge are rough in texture. The inner and outer walls show bright and dark debris streaming downslope, some of it forming broad fans. This ridge overlies and therefore must be younger than a second ridge running from top to bottom on the left side of the image. This dark ~2 km wide ridge is relatively flat, and has smaller-scale ridges and troughs along its length.

Scrambled Ice

This complex area on the side of Europa which faces away from Jupiter shows several types of features which are formed by disruptions of Europa's icy crust. North is to the top of the image and the Sun illuminates the surface from the left. The prominent wide, dark bands are up to 20 kilometers wide and over 50 kilometers long. They are believed to have formed when Europa's icy crust fractured, separated, and filled in with darker, "dirtier" ice or slush from below. A relatively rare type of feature on Europa is the 15 kilometer diameter impact crater in the lower left corner. The small number of impact craters on Europa's surface is an indication of its relatively young age. A region of chaotic terrain south of this impact crater contains crustal plates which have broken apart and rafted into new positions. Some of these "ice rafts" are nearly 1 kilometer across. Other regions of chaotic terrain are visible and indicate heating and disruption of Europa's icy crust from below. The youngest features in this scene are the long, narrow cracks in the ice which cut across all other features. One of these cracks is about 30 kilometers to the right of the impact crater and extends for hundreds of kilometers from the top to the bottom of the image.

P-49872

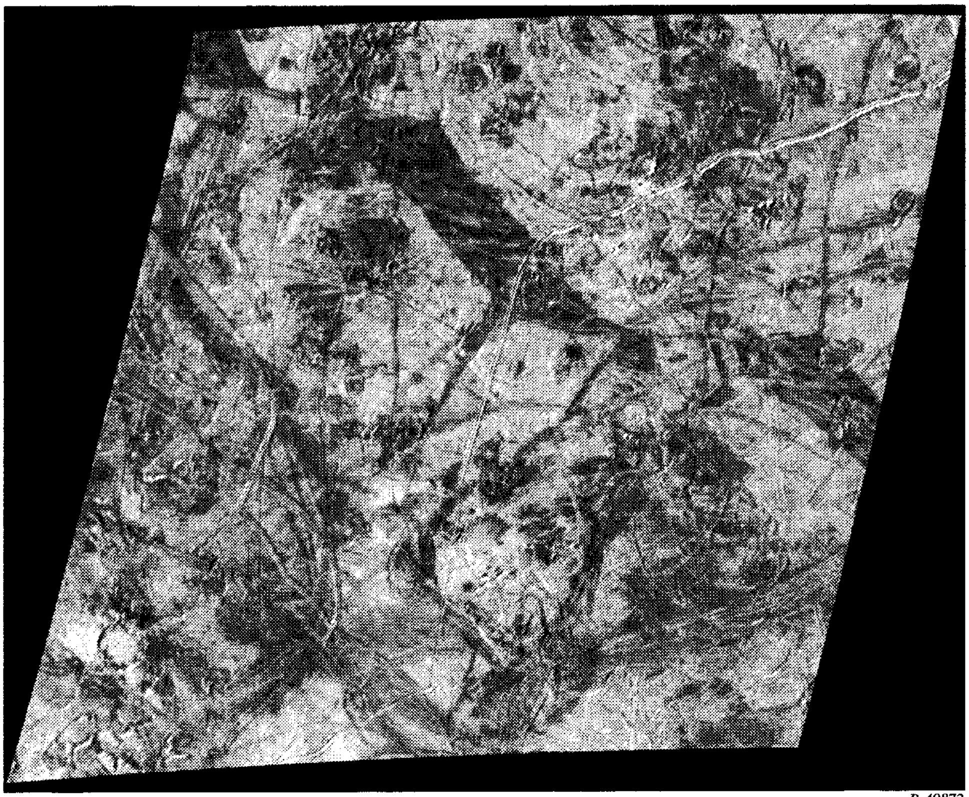
A Dark Spot on Europa

This view of Jupiter's icy moon Europa focuses on a dark, smooth region whose center is the lowest area in this image. To the west (left), it is bounded by a cliff and terraces, which might have been formed by normal faulting. The slopes toward the east (right) leading into the dark spot are gentle.

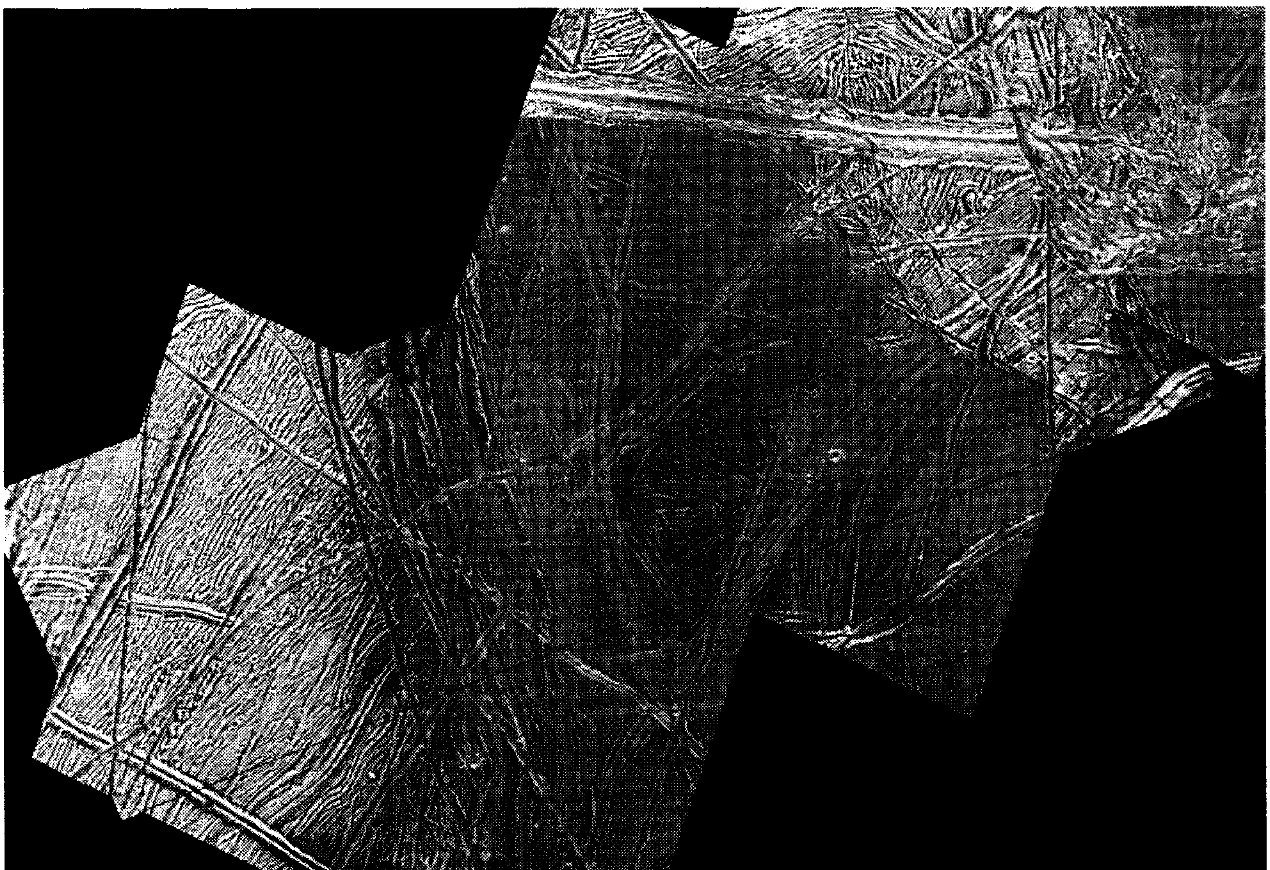
Near the center of the dark area, it appears the dark materials have covered some of the bright terrain and ridges. This suggests that when the dark material was deposited, it may have been a fluid or an icy slush.

Only a few impact craters are visible, with some of them covered or flooded by dark material. Some appear in groups, which may indicate that they are secondary craters formed by debris excavated during a larger impact event. A potential source for these is the nearby crater Mannann'an.

P-49885



P-49872



P-49885